The Ocean's "Garbage Patches": What They Are and How They Impact the Ocean Ecosystem

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Cover Photo:
A tangle of lost fishing gear, known as a "ghost net," floats on the surface of the North Pacific Subtropical Gyre. Ghost nets such as this are known to entangle and kill marine animals. However, most of the plastic in the North Pacific Subtropical Gyre are tiny particles less than 1 cm in size.

TABLE OF CONTENTS

A Selection of Terms to Know 4

PART 1: THE SCIENCE BEHIND THE OCEAN'S "GARBAGE PATCHES" 5

What a "Garbage Patch" is and What it is Not 5

- Where Does Ocean Litter Come From? Why is it Primarily Composed of Plastic and Not Other Materials? 5

How Does a "Garbage Patch" Form? 8

How Big are the Observed Accumulation Zones in the Ocean? How Much Plastic is in these Regions? 12

- Is the Amount of Floating Marine Debris in the Open Ocean Increasing Over Time? What Ultimately Happens to the Plastic Debris? 13

Current Research and Solutions 14

Works Cited 15

PART 2: IMPACT OF PLASTIC ON THE OCEAN ECOSYSTEM 17

Review of the Characteristics of Plastics 17

Research on the Impact of Plastic on the Ocean 17

Debris: Large and Small 17

Macrodebris: Entanglement 19

- Direct Entanglement 19
- Ghost Fishing 19
- Habitat Damage 20

Ingestion in Vertebrates 20

Microdebris: Ingestion in Small Fishes and Invertebrates 21

Microdebris: Toxins 23

Rafting and Introduction of Invasive Species 23

Can It Be Cleaned Up? 24

What Else Is Being Done? 25

- Technological solutions 25
- Legislation 25
- Prevention 26

What Can You Do? 26

Works Cited 27

About The Authors 29

A SELECTION OF TERMS TO KNOW

Adsorption (p. 23) The binding of molecules to a surface.

Biofilms (p. 5) An aggregation of microorganisms that adhere to a surface, such as a piece of marine debris.

Bisphenol-A (BPA) (p. 17) A plastic additive primarily used in polycarbonate and epoxy products, such as food packaging, metal can liners, and medical devices.

Ekman transport (p. 10) The net transport of water in the near-surface ocean in direct response to the wind. Ocean theory predicts the net transport to be 90° to the right of the wind in the northern hemisphere, and 90° to the left of the wind in the southern hemisphere.

Ghost nets (p. 19) Lost or discarded fishing gear, which can continue to trap and kill marine life.

Landfill leachate (p. 23) Liquid that drains from a landfill. This may be due to precipitation, natural surface water flow, or decomposition within the landfill. These liquids can contain many pollutants and toxic substances, and can contaminate surface and groundwater if not properly contained.

Macrodebris (p. 17) Debris pieces greater than 5 mm in size. Macrodebris includes everything from plastic drink containers to shipping containers. It can therefore be relatively small or extremely large.

Marine debris (p. 5) Any solid man-made material that is manufactured or processed that persists in the marine environment.

Marine debris accumulation zones (p. 5) Regions of the ocean in which floating marine debris has been observed to accumulate due to a convergence in the ocean surface currents that transport the debris.

Microdebris (p. 7) Marine debris between 0.3 and 5 millimeters in size. Operational definition based on the mesh size of the plankton nets typically used to measure marine debris.

Mixed layer (p. 13) The layer in which surface turbulence from the wind or other processes vertically mixes the water column, resulting in a layer of near-constant temperature, salinity, and density.

Monofilament (p. 21) Fishing line made from a single strand of plastic. Monofilament is made by melting plastic polymers and then forcing the mixture through tiny holes, forming a long, thin strand.

Neuston (p. 8) The group of organisms that are found at the air-sea interface, either floating on the surface film of water or attached beneath it.

Phthalates (p. 17) A family of chemicals added to plastics, particularly vinyl, to make it soft and flexible.

Photothermal oxidation (p. 18) The chemical breakdown of plastic due to sunlight, particularly ultraviolet light, and heat absorption.

Plasticizer (p. 17) A substance added to plastic to change its physical properties, such as to increase flexibility or strength.

Polylactic acid (PLA) (p. 25) A type of plastic made from corn or other biological material. PLA is biodegradable in industrial composting facilities, but not in the ocean.

Polymer (p. 6) A natural or synthetic macromolecule (large molecule) that is composed of repeating structural units. Most plastic polymers have a backbone composed of carbon atoms.

Primary microdebris (p. 7) Microdebris whose manufactured size is less than 5 mm.

Secondary microdebris (p. 7) Microdebris that results from the physical breakdown of items larger than 5 mm in size.

Subtropical convergence zone (p. 10) A region of converging surface currents resulting from Ekman transport that typically occurs near 30° latitude, the boundary between tropical trade winds and mid-latitude westerly winds.

Subtropical gyre (p. 8) A system of rotating currents occurring in each of the subtropical ocean basins (North and South Atlantic, North and South Pacific, and Indian Oceans) that is clockwise in the northern hemisphere and counterclockwise in the southern hemisphere. This flow is driven by the wind blowing over the surface of the ocean and the Earth's rotation.

Subtropical ocean basins (p. 8) Regions of the ocean between approximately 15–45° latitude in which subtropical gyres are the predominant circulation pattern.

Zooplankton (p. 21) Tiny, free-floating animals that cannot swim against the water's horizontal currents. Zooplankton are a diverse group of animals that includes crustaceans, larval fishes, jellies, mollusks, and worms.

PART 1
THE SCIENCE BEHIND THE OCEAN'S "GARBAGE PATCHES"

Kara Lavender Law, Sea Education Association (SEA)

What a "Garbage Patch" is and What it is Not

You may have heard of the "Great Pacific Garbage Patch", and perhaps also the more recently-dubbed "Great Atlantic Garbage Patch". Litter floating in the open ocean is one of the most publically recognized environmental issues specific to the ocean. But what exactly are these ocean phenomena, and what effects are they having on the ocean ecosystem?

Let's begin with what a "garbage patch" is and what it is not. Imagery commonly associated with this term includes a "floating landfill" of garbage, or a plastic "island" of trash that is so dense with material that one could practically walk across it. While these misconceptions are very common, they are completely inaccurate. Instead, in very specific regions of the North Atlantic, North Pacific, and possibly other **subtropical ocean basins**, high concentrations of tiny fragments of debris, primarily composed of plastic, float on the sea surface. These bits of litter are transported to the subtropical basins by ocean surface currents.

While the total amount of floating plastic likely measures in the thousands of tons or more, the vast majority of this debris is not even visible by eye to an observer on the deck of a ship, let alone from an airplane or satellite. There are no distinct boundaries to these regions—they are not really "patches" at all—because of the inherent variation in ocean currents, and also the varied and ever-changing sources of litter to the ocean. To keep this distinction in mind, we will instead refer to these regions as **marine debris accumulation zones.** The nature of the litter itself, together with the remoteness of the open ocean, make marine debris difficult to measure, and therefore difficult to study. Far more questions remain about this environmental problem than have yet been answered.

Where Does Ocean Litter Come From? Why is it Primarily Composed of Plastic and Not Other Materials?

The definition of **marine debris** is any solid manufactured or processed material that persists in the marine environment. The marine environment includes beaches, shorelines, bays, estuaries, and the open ocean. Marine debris, or marine litter, may be made of glass, metal, plastic, or other materials that typically comprise common everyday items such as bags, bottles, cans, packaging, and cigarette butts. It may also have commercial or industrial origins—fishing gear, aquaculture materials, and industrial resin pellets (the "raw material" of manufactured plastic goods) are some examples.

Marine debris enters the ocean from land and from vessels and platforms at sea. The rising tide sweeps up trash left on the beach; rivers, waterways, and sewage and drainage outflows ultimately drain their contents into the ocean; and winds, especially during storms, carry debris out to sea. Ships and at-sea platforms are required to follow international regulations on disposal of garbage and other waste, including a strict ban on the dumping of plastic anywhere in the ocean (Figure 1). But accidental and intentional dumping still occurs. Enforcement of these ocean-wide regulations is an extremely difficult logistical challenge.

The material properties of litter determine where in the ocean it will ultimately reside, as well as its ability to degrade in the marine environment. Materials with a density greater than the density of seawater (~1.026 km/m^3) will sink to the seafloor, while materials less dense than seawater will float. Items that will ultimately sink in the ocean include steel cans, glass bottles, and some types of plastic goods that are denser than seawater. The plastic resin code stamped on many types of consumer packaging (often referred to as a "recycling code") indicates the type of plastic material. (Table 1)

Plastics denser than seawater include polyethylene terephthalate (PET, #1), polyvinyl chloride (PVC, #3), and solid polystyrene (PS, #6)—you may recognize these as soft drink bottles, garden hoses, building materials, takeout food containers, and disposable cutlery, for example. Other types of plastic are less dense than seawater and will initially float at the sea surface. The most common materials observed at the ocean surface are high and low density polyethylene (HDPE, #2 and LDPE, #4) and polypropylene (PP, #5)[1]. These materials are used to make grocery bags, milk bottles, dairy containers, and drinking straws—products now ubiquitous around the world. There is some evidence that the density of plastic can change after exposure to marine conditions. The growth of **biofilms** and encrusting organisms, for example, may increase the density enough to cause sinking away from the sea surface.

The degradability of a material in the ocean will determine whether or not trash is a temporary presence, or

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Table 1 Plastic resin codes, the type of material they refer to, and examples of products that are made from virgin resins or recycled content. Information from the American Chemistry Council. http://www.americanchemistry.com/s_plastics/bin.asp?CID=1102&DID=4645&DOC=FILE.PDF

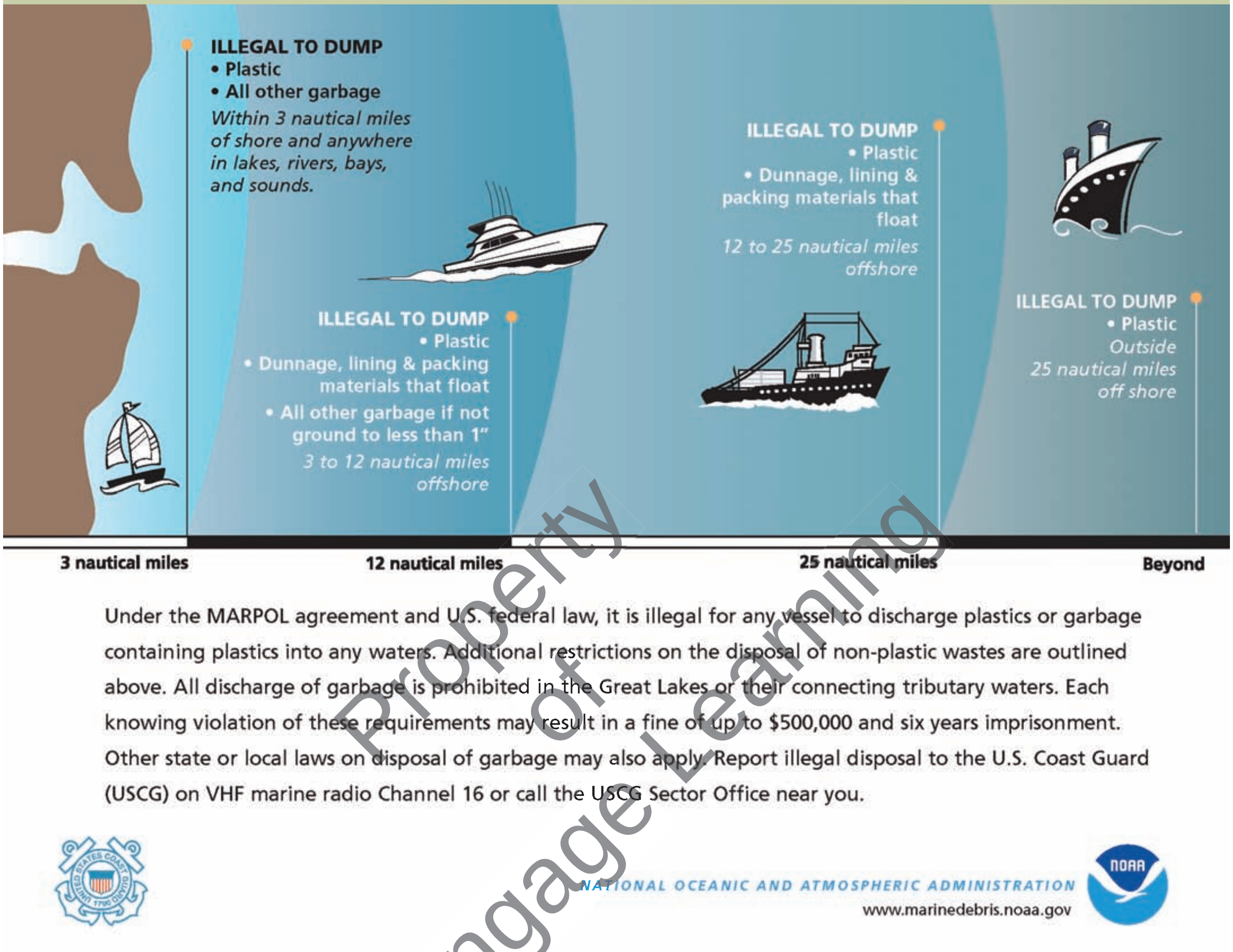
Plastic Resin Code	Name of plastic material	Examples of plastic products
1 PETE	Polyethylene Terephthalate (**PET, PETE**)	• Soft drink, water, and juice bottles • Peanut butter, jelly, and pickle jars • Microwavable food trays • Fibers for textiles, carpet, fleece
2 HDPE	High Density Polyethylene (**HDPE**)	• Milk, water, and juice bottles • Shampoo, dish and laundry detergent, and household cleaner bottles • Grocery bags • Plastic lumber for decking and fencing • Buckets, crates, flower pots
3 V	Polyvinyl Chloride (**PVC, Vinyl**)	• Deli and meat wrap • Blister pack and clamshell packaging • Pipe, decking, fencing, gutters, garden hose • Medical products (e.g. blood bags, tubing)
4 LDPE	Low Density Polyethylene (**LDPE**)	• Dry cleaning, newspaper, produce, and bread bags • Container lids • Coatings for paper milk cartons, beverage cups • Trash cans, compost bins, outdoor lumber
5 PP	Polypropylene (**PP**)	• Yogurt, margarine, and takeout containers • Bottle caps • Medicine bottles • Brooms, brushes, ice scrapers, storage bins
6 PS	Polystyrene (**PS**)	• Meat and poultry trays • Disposable cups, plates, bowls, cutlery • Protective foam packaging, packing peanuts • Light switch plates, rulers, license plate frames
7 OTHER	**Other**. All other plastic resins, or a combination of resins	• Oven-baking bags • Custom packaging • Plastic lumber

whether it becomes persistent marine debris. While paper, natural fibers, and organic material such as food waste may degrade relatively quickly in the ocean, the majority of waste, including metal, glass, and plastic, may take tens to hundreds of years or longer to degrade in the ocean. This makes it essentially "permanent" with respect to a human lifetime.

Plastic may physically break down into smaller pieces when exposure to sunlight, heat, and water causes the material to become weak and brittle over time. Even the **polymer** molecules themselves may break down into smaller chains through these degradation reactions. But full degradation does not occur unless the molecules have been broken down into the basic building blocks of carbon dioxide, water, and small inorganic molecules, a process mediated by microorganisms that use carbon in the polymer chain as an energy source.

We do not know how long, if ever, it will take for different plastic materials to fully degrade in the ocean. While some plastic materials are now being touted as "biodegradable", there is currently no reliable standard to evaluate this claim. Even if some of these materials undergo full degradation, the degradation is specific to a particular environment

▶ **Figure 1** International maritime regulations instituted in 1988 (MARPOL Annex V of the International Maritime Organization) specify rules for the disposal of garbage from ships at sea. Ships 26 feet in length and longer are required to post a placard notifying passengers and crew of these requirements. By these regulations, disposal of any plastic material into the sea is banned. Image courtesy of the NOAA Marine Debris Program



such as a composting facility or the soil. It is not known if these compostable materials will ever fully break down in the marine environment, let alone those materials that degrade only partially or not at all in a terrestrial environment.

In the open ocean, the low density and inherent resistance to degradation of polyethylenes and polypropylene cause these materials to be the most abundant type of marine debris floating at the sea surface. While large, often identifiable objects such as crates, shoes, toothbrushes, fishing buoys, and jugs may be observed from ships in the accumulation zones, the majority of debris is **microdebris**, operationally defined as 0.3–5 millimeters in size based on the mesh size of the nets used to collect it. Manufactured items smaller than 5 millimeters, known as **primary microdebris**, include industrial resin pellets (Figure 2) and plastic spherules used in health and beauty products such as facial cleansers. However, presumably because of the physical deterioration caused by exposure to sunlight and the high-energy ocean environment, the majority of particles collected at the sea surface are classified as **secondary**

▶ **Figure 2** Photograph of plastic resin pellets that are the industrially produced "raw material" of manufactured plastic goods. Pellets are typically cylindrical or spherical with a diameter of a few millimeters.

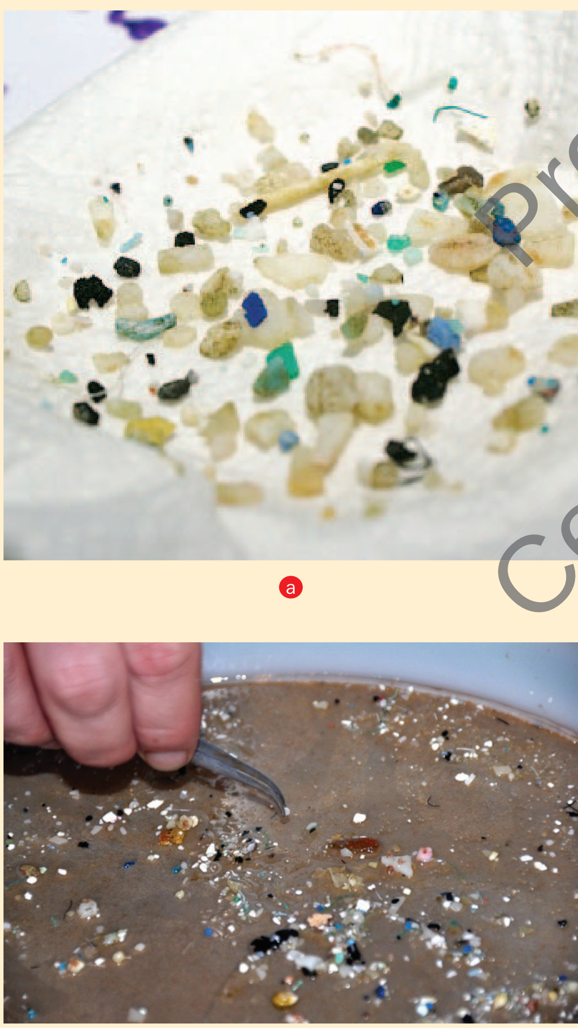
▶ Photograph courtesy of Hideshige Takada and International Pellet Watch (www.pelletwatch.org).

microdebris, fragments formed by the physical breakdown of once-larger items (Figure 3). In general, the source of the litter cannot be determined from the millimeter-sized fragments themselves—the type of object and its history remain unknown.

How Does a "Garbage Patch" Form?

How do we know where marine debris accumulates in the ocean? Why does it collect in these particular regions? Plastic marine debris was first reported in the western North Atlantic Ocean in the early 1970s by researchers who found small plastic particles in plankton nets that had been towed at the sea surface. Plankton net tows are still the most commonly used method to measure floating debris. The neuston net and manta net (Figure 4) are both designed to sample the **neuston** layer of the ocean, or the air-sea interface. The net is towed with its mouth partially submerged in the water, typically sampling the top one-half meter of the ocean or less. Designed to collect zooplankton, the mesh on these nets is typically ~335 μm (0.3 mm) in size, the basis for the operational definition of microdebris. After towing the net at the sea surface, pieces of debris are hand-picked from the net contents, counted, and sometimes dried and weighed.

▶ **Figure 3** Photographs of plastic microdebris collected in the eastern North Pacific and western North Atlantic Oceans. Debris is typically composed of fragments of plastic that are millimeters in size and a variety of colors. Top photo shows a Petri dish with 240 pieces of debris (equivalent to ~200,000 pieces per square kilometer) collected in one plankton net tow.



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b

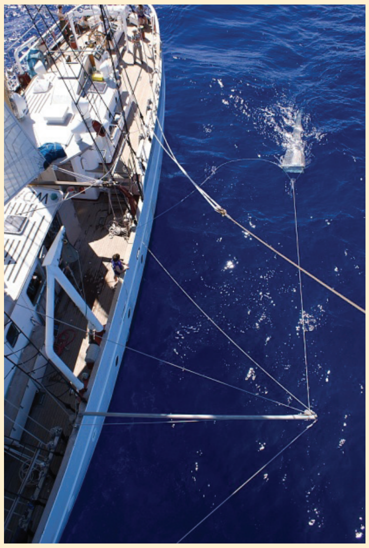
▶ Giora Proskurowski/Sea Education Association, Marilou Maglione/Sea Education Association

The abundance of debris has been reported in a variety of units, either as number of pieces per unit area or per unit volume, or mass per unit area or per unit volume. The number of pieces of debris typically collected in one net tow in an accumulation zone is highly variable. In one study[2], the maximum number of pieces collected in a 30-minute plankton net tow was 1069 (equivalent to 580,000 pieces per square kilometer). However, more typical tows contained only 20 pieces (11,000 pieces per square kilometer). Twenty pieces of millimeter-size fragments together typically weigh less than one gram, the weight of a one dollar bill.

One misconception about marine debris is that trash is ubiquitous in the global ocean—that no matter where you go you will see household items bobbing at the sea surface. Not only is this false because most debris is too small to be visible, but also because very little microdebris has been observed outside of the major accumulation zones. From thousands of plankton net tows in the Atlantic and Pacific Oceans, it has been determined that plastic microdebris is found in high concentrations primarily in the subtropical ocean basins. In a study in the western North Atlantic[1], for example, more than 80% of plastic pieces collected between the Caribbean Sea and Newfoundland, Canada were collected between 22°N and 38°N, roughly the latitudes from Cuba to Washington, D.C (Figure 5). Outside of this latitude band the average concentration of plastic debris was relatively low, or in many cases even zero. This geographic region of the western North Atlantic is also known as the Sargasso Sea, named for the floating *Sargassum* seaweed (macroalgae) that grows there. Oceanographically, this region corresponds to the **North Atlantic subtropical gyre**, a clockwise ocean circulation feature driven by the winds blowing over the ocean surface (Figure 6).

Global winds are ultimately driven by the uneven heating of the Earth by the sun, and by the Coriolis effect resulting from the rotation of the Earth. Easterly winds (blowing east to west) that typically occur in the tropics are the trade winds, while westerlies typically occur in mid-latitudes. The approximate boundary between these predominant wind patterns occurs near 30° latitude, where the winds are characteristically weak and variable.

Figure 4 Neuston net (a, b) towed at the air-sea interface to collect plankton and marine debris larger than 335 μm in size. The net opening is 1 x 0.5 meter, and the net is towed alongside the ship as shown. A 'manta net' (c) is also used to sample the air-sea interface for floating marine debris.



Giora Proskurowski/Sea Education Association.

a

Leslie Peate/Sea Education Association

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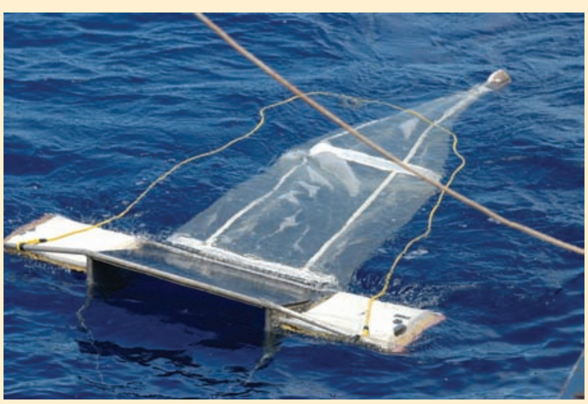
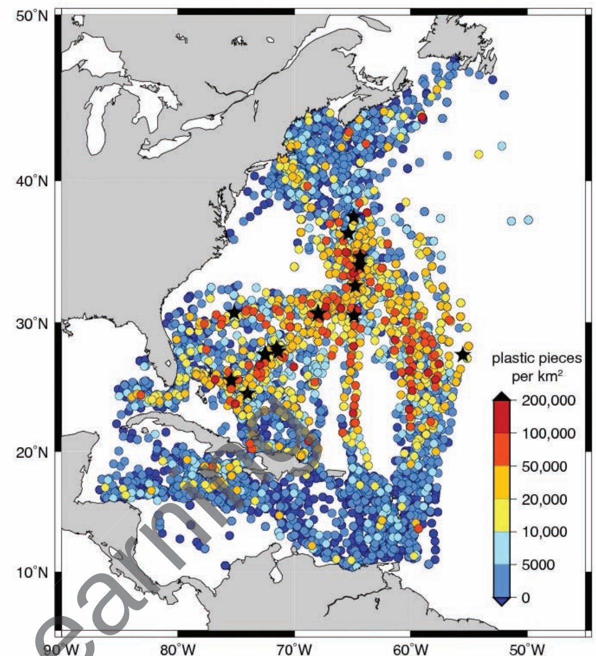


Image courtesy of Scripps Institution of Oceanography.

c

Figure 5 Distribution and abundance of plastic marine debris collected in more than 6000 neuston net tows in the western North Atlantic Ocean and Caribbean Sea from 1986 to 2008 by Sea Education Association. Symbols indicate location of net tow; color indicates concentration of plastic microdebris in units of pieces per square kilometer. Black stars indicate tows with measured concentration greater than 200,000 pieces per square kilometer. More than 80% of the 64,000+ plastic pieces were collected between 22°N and 38°N.

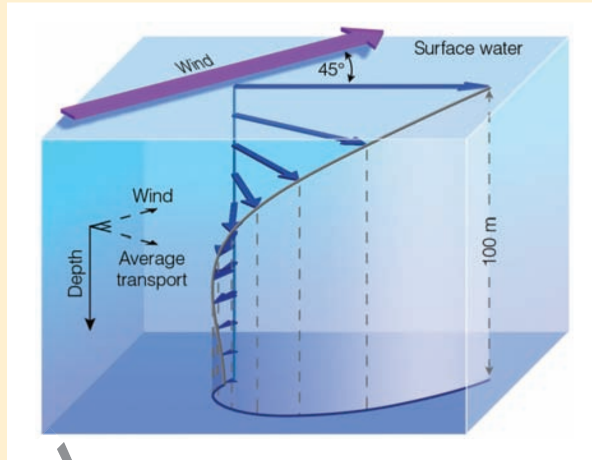


From Law et al., Plastic Accumulation in the North Atlantic Subtropical Gyre, *Science* 3 September 2010: 329 (5996), 1185–1188. Published online 19 August 2010 [DOI:10.1126/science.1192321]. Reprinted with permission from AAAS.

Figure 6 The North Atlantic subtropical gyre is a clockwise flow ultimately driven by surface winds. The boundary between the easterly trade winds in the tropics and the mid-latitude westerlies is typically around 30°N latitude, in the center of the gyre. The gyre is described by four major currents—the Gulf Stream, the North Atlantic Current, the Canary Current, and the North Equatorial Current.

The wind is one of the major forces that cause ocean currents, the movement of water that is analogous to wind in the atmosphere. When the wind blows over the surface of the ocean, the friction between the moving air and the water below causes the surface layer of the ocean to begin moving in the same direction as the wind. But the rotation of the Earth causes this layer to deviate from its initial direction of flow, turning to the right of the wind direction in the northern hemisphere, and to the left of the wind direction in the southern hemisphere. This phenomenon continues down the water column as one "layer" of water causes the layer beneath it to move. Ultimately, the friction within the water column and the deviation in flow direction caused by the Coriolis effect cause the water in the upper few hundred meters of the ocean to collectively move 90° to the right of the wind in the northern hemisphere (to the left in the southern hemisphere), a phenomenon known as **Ekman transport**. (Figure 7)

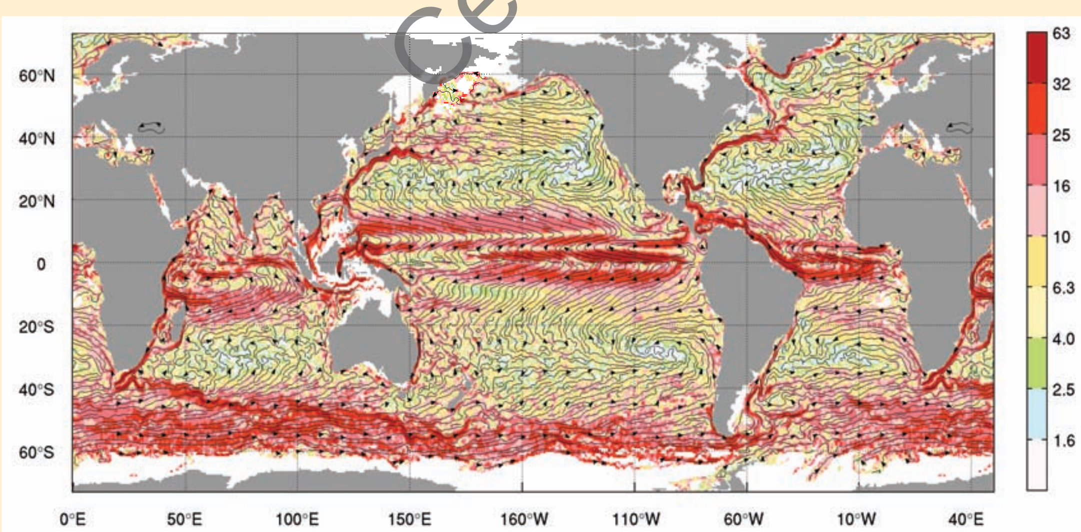
► **Figure 7** The Ekman Spiral. Winds move the water, and the Coriolis force deflects the water to the right (Northern Hemisphere). Below the surface each successive layer of water moves more slowly and is deflected to the right of the layer above. The average transport of surface water in the Ekman layer is at right angles to the prevailing winds.



Therefore, upper ocean water in the mid-latitudes (approximately 30° to 60° latitude) moves towards the equator, while in the tropics (0° to 30°) it moves towards the poles, causing water to "converge", or come together, at the 30° latitude boundary. This convergence, primarily resulting from Ekman transport, is referred to as the **subtropical convergence zone**. Not only does the water in the surface layer converge, but so does anything floating at the sea surface, such as *Sargassum*, plastic or other floating marine debris, or natural debris such as wood that found its way into the ocean.

Subtropical convergence zones are observed in each of the subtropical ocean basins. Using state-of-the-art ocean measurement techniques, researchers have created a map of the average surface circulation of the ocean[3] (Figure 8). While real ocean current patterns are not quite as simple as the cartoons drawn to illustrate ocean theory, the major characteristics are present. In the subtropics of the North Atlantic, for example, there is a large-scale clockwise flow with maximum current speeds observed in the western boundary current, the Gulf Stream. Near the center of the gyre, the surface currents from the north and south converge at 30°N where current speeds are at a minimum (less

► **Figure 8** Average surface circulation of the ocean computed using data from surface drifting buoys, satellite altimetry, hydrographic profiles, and reanalysis wind data, from the period 1993–2002. Black lines indicate streamlines, with arrows indicating direction of flow. Colors indicate speed of surface current in units of centimeters per second. In the subtropical North Atlantic Ocean currents are generally clockwise, but flow converges near 30°N latitude where current speeds are less than 2 cm/s. This region is the subtropical convergence zone, where high concentrations of marine debris are observed. Notice similar characteristics of the gyres in other subtropical ocean basins.

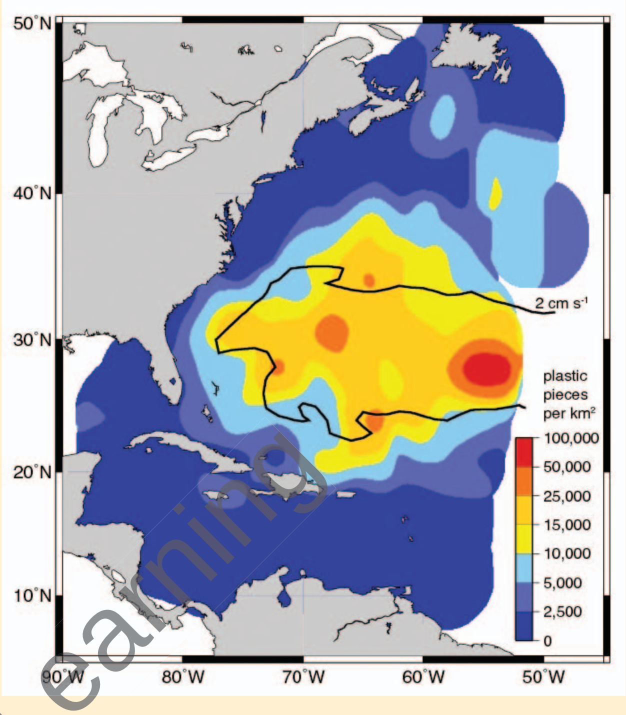


than 2 cm/s). This is the subtropical convergence zone where, based on theory and observation, one would expect to find high concentrations of floating marine debris.

In fact, subtropical convergence zones are where high plastic concentrations have been observed in both the western North Atlantic (Figure 9) and the eastern North Pacific Oceans on many research expeditions. A numerical modeling study[4] also confirms the notion that floating debris accumulates in subtropical convergence zones. In this model, the ocean was initially covered with a uniform concentration of floating "debris". The movement of the surface currents, and therefore the passively-drifting debris, was determined from observations of real ocean surface currents. As the model was run, the debris was observed to accumulate in the subtropical gyres as a result of the converging surface currents (Figure 10). This predicted accumulation has already been confirmed by measurements of plastic debris in both the North Atlantic and North Pacific Oceans. Future expeditions are planned to explore the subtropical gyres in the South Atlantic, South Pacific, and Indian Oceans, where the model predicts debris will also accumulate.

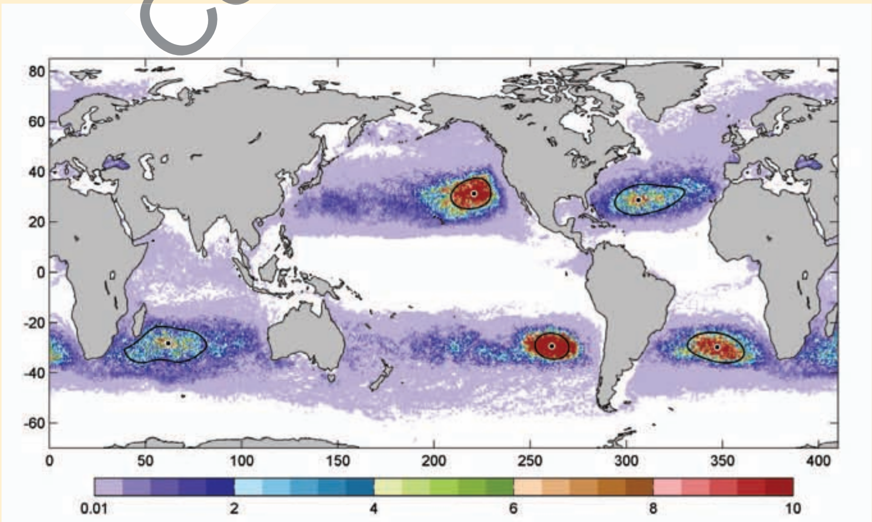
While a very nice, simple picture emerges from these studies, it is important to note that the ocean, even in the subtropical gyres, does not have a uniformly high concentration of marine debris. Even where the highest amounts of marine debris have been measured, there is significant variation from one net tow sample to the next. It is not unusual to have one sample with hundreds of pieces of plastic microdebris, and another just 50 or 100 miles away with very few pieces. This illustrates how the ocean behaves in a far more complex manner than described by the simple

▶ **Figure 9** Average concentration of plastic marine debris (color shading) computed from the data in Figure 6. Black line indicates 2 cm/s contour of surface current velocity from data in Figure 8, corresponding to the subtropical convergence zone. There is a very strong correspondence between the highest observed plastic concentration and the converging surface currents that act to concentrate the debris.



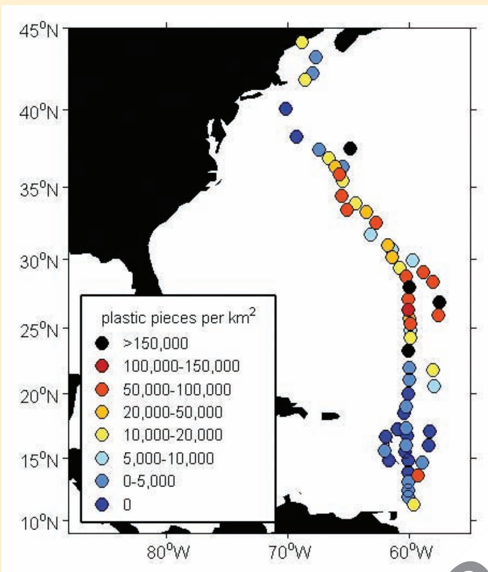
▶ Credit: From Law et al., Plastic Accumulation in the North Atlantic Subtropical Gyre, *Science* 3 September 2010: 329 (5996), 1185–1188. Published online 19 August 2010 [DOI:10.1126/science.1192321]. Reprinted with permission from AAAS.

▶ **Figure 10** Numerical model simulation of the concentration of surface "debris". Debris was initially uniformly distributed on the ocean surface, and then allowed to drift with the surface currents for a period of ten model years. Color shading indicates the relative concentration of debris with respect to an initial value of one. The resulting distribution predicts that debris accumulates in the subtropical gyres in the North and South Atlantic, North and South Pacific, and Indian Oceans. The accumulation zones are comparable in size, but vary in strength of convergence and therefore in concentration of debris. Note that because real debris sources are not uniformly distributed around the globe, this model does not represent actual measurements of debris in the ocean.



▶ Figure reprinted with permission from *Oceanography*, v. 23, no. 4, p. 94–103, Fig. 4, http://tos.org/oceanography/articles/23-4_dohan.pdf

▶ **Figure 11** Distribution and abundance of plastic marine debris collected on two simultaneous cruises in fall 1993. The R/V *Westward* and the SSV *Corwith Cramer* of Sea Education Association measured plastic marine debris along parallel cruise tracks from Woods Hole, MA to St. Croix, US Virgin Islands. Symbols indicate location of neuston net tows, and color indicates concentration of plastic microdebris in units of pieces per square kilometer. While the highest concentrations of plastic were found in the subtropics, large variability was observed from tow to tow. Notice concentrations from neighboring net tows near 23°N and 36°N ranging from less than 5,000 pieces km^{-2} to greater than 150,000 pieces km^{-2}.



▶ Data courtesy of Sea Education Association

▶ **Figure 12** SSV *Corwith Cramer*, a sailing oceanographic research vessel operated by Sea Education Association. During six week cruises onboard the *Cramer*, students in the SEA Semester® program sail the ship and collect oceanographic data, including plastic marine debris data, for their independent student research projects. www.sea.edu

▶ Roman Shor/Sea Education Association

theory above. While the basic prediction of large accumulation zones is accurate, the actual variation in winds, ocean currents, and other parameters such as the sources of marine debris cause large variations in observed plastic concentration, even on a single research cruise (Figure 11). Thus, while we may know where to look for high concentrations of floating debris, there is no guarantee that any given net tow sample will actually contain debris.

How Big are the Observed Accumulation Zones in the Ocean? How Much Plastic is in these Regions?

These are important questions that are very difficult to answer. To determine how large an accumulation zone is, the edges of the region must be defined in some way using ocean measurements. Since the debris in these regions is not typically visible, the only way currently used to measure floating debris is by collection with plankton nets onboard ships. This is an arduous and expensive task given the size of the subtropical ocean basins that must be surveyed, and the cost of operating an ocean-going vessel. In addition, because of the inherent variation within the ocean itself, only after repeated surveys over a period of years can one begin to assess the general size of a region of debris accumulation.

The most extensive data set in any ocean basin has been collected by Sea Education Association (SEA, Woods Hole, MA) in the western North Atlantic. Since the 1970s, undergraduate students in the SEA Semester® program have sailed as crew members aboard SEA's sailing oceanographic research vessels (Figure 12), collecting data during six-week cruises to support their independent student research projects. Routine oceanographic sampling includes twice daily tows of a neuston net to collect plankton samples and marine debris. Sailing the same cruise tracks year after year, more than 7000 students and faculty scientists have conducted more than 6000 net tows from the Caribbean Sea to Newfoundland, resulting in a plastic marine debris data set that has allowed researchers to address basic questions about the abundance and distribution of plastic debris, and how they have changed over time.

From the SEA surveys an estimated 6.7 million square kilometers of the western North Atlantic has a plastic concentration greater than 2,500 pieces per square kilometer, representing a total of 1,100 metric tons of plastic debris. While this area is roughly twice the size of India, it is important to note that this represents a *minimum* first-guess estimate. This is because there were no available measurements from the eastern two-thirds of the North Atlantic basin. In 2010, the Plastics at SEA: North Atlantic Expedition[5] found high concentrations of plastic debris along the 30°N parallel from Bermuda to the center of the Atlantic basin at 40°W longitude. These data supported the hypothesized high concentrations of debris predicted from surface current measurements and numerical model results. Therefore, it is certain that the North Atlantic accumulation region is larger than the estimate above, although no one knows by exactly how much.

In the North Pacific Ocean, high concentrations of marine debris have been found across the basin from Japan to the west coast of the United States in subtropical latitudes (~30°N-40°N). The highest concentrations have been observed in the western basin a few hundred kilometers east of Japan, and in the eastern North Pacific between Hawai'i and the west coast of the United States. In these regions floating plastic debris has been observed in similar concentrations as in the western North Atlantic Ocean. Even though the first reports of marine debris in the North Pacific were made in the 1970s, and media attention has focused heavily on the eastern North Pacific region, relatively sparse ship surveys and limited data make it extremely difficult to estimate the size of any accumulation zones, or the amount of plastic debris floating within. Results from the numerical model discussed earlier suggest that the major accumulation zone in the eastern North Pacific is comparable in size to that in the North Atlantic. However, this prediction must be confirmed with oceanographic data.

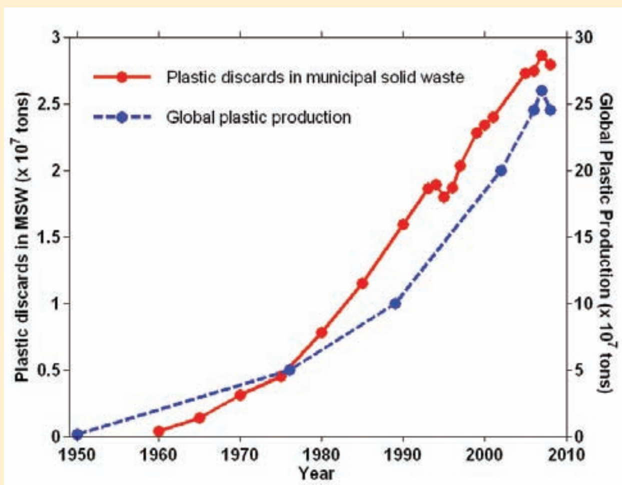
Our discussion thus far has focused on marine debris floating at the sea surface. To date, the majority of measurements of marine debris in the open ocean have been made using plankton nets designed to sample the air-sea interface. Limited samples have also been collected using plankton nets towed from the sea surface to a depth of 20 meters, in both the eastern North Pacific and western North Atlantic Oceans. In many cases, plastic fragments were also found suspended in this near-surface portion of the water column that typically includes the mixed layer. The **mixed layer** is formed when energy from the wind or other processes mixes the water column vertically, resulting in a surface layer of essentially constant temperature, salinity, and density. It appears that the energy supplied by the wind can mix even buoyant plastic fragments below the sea surface. This means that estimates of plastic concentration from all but the calmest of wind and sea conditions most likely underestimate the total amount of plastic in the near-surface layer.

Is the Amount of Floating Marine Debris in the Open Ocean Increasing Over Time? What Ultimately Happens to the Plastic Debris?

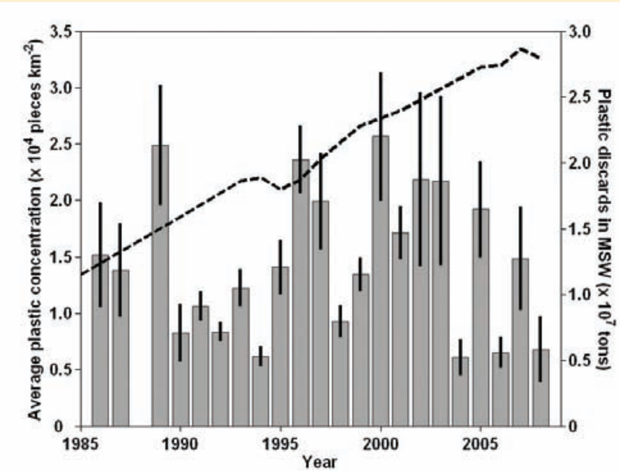
The amount of marine debris at the sea surface is determined by two factors: how much floating debris enters the ocean, and how much eventually leaves the surface layer after exposure to ocean conditions. The amount of debris entering the ocean has not been directly measured because of the inherent difficulty in quantifying the widespread and variable sources. While some types of pollution are fairly easy to measure, such as the emission from a smokestack or drainage from a pipe, marine debris enters the ocean from many different sources that are difficult to monitor. Beach surveys can provide information for a particular beach, but how does one estimate the input of debris from the wind during storms? Or the dumping of plastic trash from ships, which is banned, but which certainly still occurs? Instead, records of global plastic production and discarded plastic in the United States municipal waste stream, defined as waste generated minus removal for recycling, have been used to infer a likely increase in plastic litter entering the ocean since the 1960s (Figure 13).

In most parts of the ocean, including the eastern North Pacific, there are simply not enough data to reliably estimate a trend in the concentration of marine debris over time. However, in the western North Atlantic Ocean data collected by Sea Education Association on annually-repeated cruise tracks were analyzed to determine whether the concentration of floating plastic marine debris changed from 1986 to 2008[2]. Given the likely increase in plastic waste to the ocean during this time period, one might expect to find an increase in plastic debris in the region where it is found to accumulate. Instead, annual averages revealed a large amount of variability from year to year with no clear increase observed (Figure 14). A similar result was found in waters between the British Isles and Iceland, in which a significant increase in plastic microdebris was observed from the 1960s and 1970s to the 1980s and 1990s, but no significant increase was observed between the later decades[6]. While these surprising results could be optimistically interpreted to mean the input of

▶ **Figure 13** Records of plastic waste discarded in the United States municipal waste stream (after accounting for recycling), and global plastic production both show rapid increases since the 1950s and 1960s. Because the widespread and ever-changing sources of litter to the ocean are difficult to measure, records such as these have been used to infer an increase in plastic waste entering the ocean. Data from U.S. Environmental Protection Agency (municipal solid waste) and PlasticsEurope (global production).



► **Figure 14** Annually-averaged plastic concentration in the western North Atlantic accumulation zone from 1986–2008 (bars), and amount of plastic discarded (after recycling) in the United States municipal solid waste (MSW) stream. Large year-to-year variability was observed in the concentration of floating plastic debris, but there was no increasing trend. This was surprising given the likely increase of plastic waste into the ocean as inferred from the MSW record. MSW data from U.S. Environmental Protection Agency.



► Credit: From Law et al., Plastic Accumulation in the North Atlantic Subtropical Gyre, *Science* 3 September 2010: 329 (5996), 1185–1188. Published online 19 August 2010 [DOI:10.1126/science.1192321]. Reprinted with permission from AAAS.

marine debris to the ocean has decreased over time, it is more likely that mechanisms within the ocean explain the observed steady concentrations.

One such mechanism is the physical breakdown of the plastic fragments that is known to occur in the marine environment. In the long Atlantic record only pieces larger than 335 µm were captured in the plankton net. It is likely that over time, plastic fragments break down into even smaller particles that would ultimately pass through the mesh of the net. Thus, the plastic may still be floating at the sea surface even though it is too small to be measured with typical net measurement techniques.

There is also evidence that marine microbes form biofilms on floating plastic fragments, and that other colonizing organisms such as small invertebrates may use the fragments as a substrate. Biological growth on the plastic might ultimately render it denser than surface seawater, causing the debris to sink down into the water column where very few measurements have been made.

Various studies have also reported ingestion of plastic fragments by marine organisms ranging in size from plankton and small invertebrates to seabirds and large fish. It is not known how much plastic is removed from the surface ocean by ingestion—the organisms that ingest plastic, how much they ingest, and what happens to the plastic after it is ingested or after the organism dies are all questions that have only begun to be studied. More about these studies can by learned in the second half of this chapter.

Finally, plastic microdebris has also been frequently observed on beaches around the world. Because there is currently no method to determine the age of the plastic or its source, it is unknown whether debris originated on a particular beach or was washed ashore from the open ocean. In addition, records of beach debris show that both seasonal trends and long-term trends in the amount of debris vary by region. Therefore, it is unknown whether the beach is ultimately acting as a net source of debris to the ocean, or a net removal mechanism.

One notable and environmentally encouraging result from the analysis of SEA's 22-year North Atlantic record was an observed decrease in one component of floating marine debris—plastic resin pellets. Resin pellets are industrially produced and shipped to manufacturers of plastic goods, where they are melted and molded into consumer products. A 1993 study by the U.S. Environmental Protection Agency (EPA)[7] on plastic pellets in the marine environment identified common sources of pellets that ended up on beaches and in the ocean. Pellets that were spilled during handling and transport from producers to manufacturers either entered the sea directly, if spilled in port or lost from a ship at sea, or were washed into stormwater drains that ultimately discharged into the ocean.

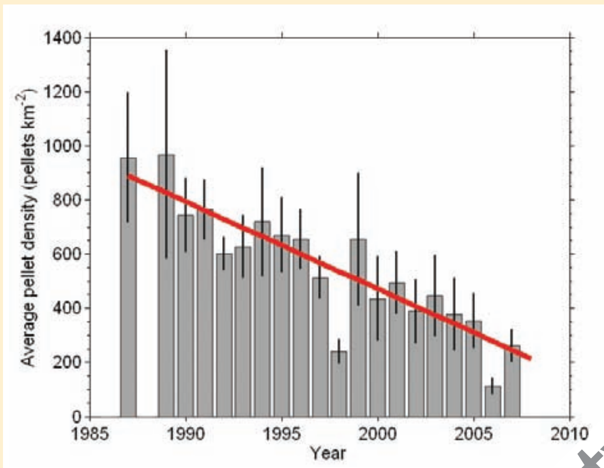
In response to these findings and earlier EPA studies, the major national trade organizations of the plastics industries voluntarily instituted the educational campaign Operation Clean Sweep in 1997[8]. This program aims to prevent or recapture spilled pellets through changes in industry practices such as improvements in packaging, installation of pellet containment systems, and inspection of pellet transport containers and vehicles.

Based on measurements of plastic resin pellets in the western North Atlantic Ocean, these industry efforts to reduce the release of pellets into the marine environment are indeed very effective. Between 1986 and 2008, a 76% decrease in the average concentration of plastic pellets was observed[2] (Figure 15). While the concentration of pellets was only a small fraction of the total amount of plastic debris collected (typically 1–16% of total pieces), this is a shining example of the positive impacts a change in land-based behavior can have on this environmental problem.

Current Research and Solutions

As you have probably noticed, even the most basic questions about marine litter in the open ocean remain: How much is there? Where is it? What ultimately happens to it? As a result of scientific research the questions have become more refined: Are there accumulation zones of marine litter in the unexplored subtropical gyre regions? Are there other physical mechanisms, such as eddies or fronts, that also act to concentrate floating marine debris? How much debris is mixed down into the water column by the wind? Is there microdebris suspended deeper in the water column, or sitting on the sea floor of the deep ocean? Is the amount of marine litter increasing over time? What ultimately

▶ **Figure 15** Annually-averaged concentration of plastic resin pellets in the western North Atlantic Ocean and Caribbean Sea. A significant 76% decrease in pellet concentration was observed from 1986 to 2008, illustrating the positive impact of the Operation Clean Sweep campaign instituted by the plastics industries in 1991. Operation Clean Sweep aims to prevent or recapture spilled pellets in the environment.



▶ Data courtesy of Sea Education Association.

happens to the debris—does it sink, is it eaten, does it wash ashore? Does it ever fully degrade in the ocean?

Now that we have established that there are no large floating landfills or mountains of trash in the ocean, one might be tempted to think that "garbage patches" are nothing more than a hyped up environmental problem. In fact, if there were such "patches" it would be relatively easy, albeit expensive, to deploy fleets of ships to clean up the problem. Instead, because the majority of litter is smaller in size than the width of a fingernail, and is relatively dilute in the ocean (a volume equivalent to more than 2,000 bathtubs of water is typically filtered to collect at most a thousand pieces of debris), there is no logistically sound way to remove this microdebris from the ocean. Even if one were to methodically transit the oceans, filtering seawater with enormous nets to remove the debris, planktonic organisms of similar size that serve critical roles in the ocean ecosystem would also be removed. A well-intentioned action could cause more damage than good. The best solution is to prevent the litter from entering the ocean in the first place.

So why is floating microdebris even a problem at all? If the microdebris is so small and relatively dilute, what are the environmental implications on the ocean ecosystem?

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PART 2
IMPACT OF PLASTIC ON THE OCEAN ECOSYSTEM

Miriam C. Goldstein, Scripps Institution of Oceanography, University of California, San Diego, SEAPLEX Chief Scientist

Review of the Characteristics of Plastics

Plastic debris is widespread throughout the world's oceans. Since plastic does not biodegrade or decompose, all the plastic that has ever entered the oceans is still there, unless it has washed up on shore. Plastic pollution is found everywhere in the world's oceans, from the coasts to remote islands to the poles. Even the deep sea and the vast open ocean is littered with trash.

This has not always been the case. The first synthetic plastic was not invented until 1907, when chemist Leo Hendrik Baekland created Bakelite out of coal tar[1]. After World War I, plastic was made of petroleum, which was easier to process into raw materials. With the discovery of over 15 new classes of polymers in the 1940s and 1950s, plastic consumer goods soon became ubiquitous[2].

Today, there are hundreds of plastic material types available and over 300 types of **plasticizer** additives[3]. Of the additives, **phthalates** and **bisphenol-A** have received the most scientific and public attention due to their potential effects on human and environmental health[4].

While plastic in the ocean is certainly a depressing and unattractive sight, it also damages marine life and marine ecosystems. Scientists began to find plastic inside the stomachs of seabirds, and to find turtles and whales entangled in plastic fishing gear[5–7]. The next section discusses what is known about the impact of plastic debris on marine life, and what remains to be discovered. At the end, potential solutions to the problem of plastic in the oceans are discussed.

Research on the Impact of Plastic on the Ocean

Scientists worldwide have made contributions to studying the problem of plastics in the ocean. These studies have examined marine debris in a large variety of habitats, from the coast to the open ocean to the deep sea. Marine debris in the open ocean, particularly in the North Pacific, has received the most media attention, but all of these studies are critical to understanding the impact that it has on our oceans. If you want to know more about any of the studies mentioned below, refer to the citations at the end of this chapter.

Many of the photos appearing in this section are from the Scripps Environmental Accumulation of Plastic Expedition (SEAPLEX), a collaboration between Scripps Institution of Oceanography at the University of California, San Diego and the nonprofit Project Kaisei. From August 2–21, 2009, a group of doctoral students and research volunteers from Scripps Institution of Oceanography at UC San Diego embarked on an expedition aboard the Scripps research vessel *New Horizon* exploring the problem of plastic in the North Pacific Gyre. SEAPLEX focused on a suite of critical scientific questions: How much plastic is accumulating in our oceans? How is it distributed? And how is it affecting ocean life? While SEAPLEX data is still being processed and the results have yet to be published in the scientific literature, the SEAPLEX researchers hope to provide insight into the problem of marine debris in open ocean ecosystems. (Figure 16).

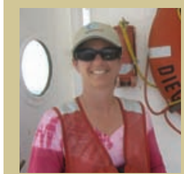
Debris: Large and Small

You have learned that plastic debris in the ocean can take two main forms: **macrodebris** and **microdebris.** To review, macrodebris is usually recognizable, and can come from either ocean-based sources, such as fishing or shipping vessels, or land-based sources, such as litter or illegal trash disposal. Items used in the sea can be fishing nets, fishing floats, traps, boat tarps, and crates. Items that might have come from land are suitcases, drink bottles, hats, and even toys (Figure 17).

▶ **Figure 16** An array of macrodebris on the deck of the *R/V New Horizon* includes pieces of discarded fishing net, crates, and bottles.

Interview with Lara Dickens

Teacher At Sea for SEAPLEX, Patrick Henry High School, San Diego Unified School District



How did a teacher end up on a scientific expedition to the middle of North Pacific?

Teachers have to get out and see what is going on if they want to keep what their teaching fresh and relevant. When the application for the Teacher at Sea program posted I jumped at the opportunity to join the Scripps researchers on their trip to the North Pacific Gyre. It is an awesome thing to be able to say that I was over a 1000 miles at sea and I saw the accumulation of plastic, and I participated in the 24-hour sampling sessions that collected bacteria, fish, phytoplankton, water, salps and soda bottles. I am thrilled to share my experience with students and other teachers in the hope that they will encourage more adventurous young people to study and protect the ocean.

What did you see out in the middle of the North Pacific Gyre?

One of my jobs on the New Horizon was to assist with the night shift manta tows. That gave me an opportunity to see the night time surface feeders; some of the most amazing and fascinating moments of my life. Bioluminescent fish and zooplankton lit up the deep black ocean. Squid and rays skimmed the surface. Even though the plastic was just as prevalent in the tows at night, it was easier to be distracted by the gorgeous glow of life.

What do you think students can do to help the ocean?

Everyone can help prevent more plastic from getting into the ocean. It can be as simple as picking up a plastic bottle cap on the ground to choosing not to purchase commercial goods made with non-biodegradable materials. Probably one of the most important and easiest things students can do is share what they know about the gyre and discuss ways to minimize plastic use with their friends.

► **Figure 17** This toy dog was found floating in a ghost net in the middle of the North Pacific.

► **Figure 18** Microdebris, including a "nurdle" (raw industrial preproduction plastic pellet located second from the left.

Microdebris is most often formed from the breakdown of larger items. While plastic, depending on its type and exposure to the sun, can become brittle in only a few years in the ocean, this does not mean that plastic can biodegrade. Most common plastics are biologically inert in the ocean, which is to say that bacteria cannot digest them into their component molecules. Most plastic in the ocean will remain plastic.

Plastic in the open ocean may weather more slowly than plastic on land for two reasons. First, the relatively cool ocean water prevents heat from building up inside the plastic and breaking down the chemical structure[8]. Second, as the plastic floats in the ocean, marine life such as algae and barnacles will usually grow on it. (See "Rafting" section). This marine growth blocks the sunlight, preventing the UV light from reaching the plastic and preventing **photothermal oxidation**[9]. Because of different rates of weathering, it is very difficult to determine how long a given particle has been in the ocean. Particle size thus cannot be directly related to amount of time in the ocean, as different particles may have experienced different conditions.

As you read earlier, both preproduction pellets and weathered particles are termed "microplastic," and are defined as having a diameter of less than 5 mm (Figure 18). Though scientists do not know how small plastic pieces in the ocean can get, pieces as small as 1/100th of an inch (1/2 mm) have been observed, though there is no reason why there could not be smaller plastic particles in the ocean.

▶ **Figure 19** Microdebris with small jellyfish (*Velella velella*). The jellyfish are about the size of a quarter.

▶ © 2009 Scripps Institution of Oceanography/UC San Diego Photo credit: J. Leichter.

Macrodebris: Entanglement

Direct Entanglement

When pieces of net or line are lost at sea, animals such as sea turtles, seabirds, and marine mammals can become entangled in them. Entanglement is estimated to affect over 267 species worldwide[10]. Entanglement primarily is caused by discarded fishing gear, though consumer products such as six-pack rings and packing straps have also been observed[10].

Entanglement affects large and small animals differently. Animals, such as sea turtles or seals, can drown or suffocate when they become entangled because they cannot get to the surface to breathe. When large animals such as whales become entangled, they drag the debris along with them, and may slowly starve because they are unable to swim fast enough to find food. In both cases, wounds caused by the debris can become infected, leading to illness or death. (Figure 20)

Scientists know the most about entanglement for animals that live part of their lives on shore, such as seabirds that come to islands to raise their chicks, or turtles that lay their eggs on sandy beaches. This is because it is hard to observe animals that spend their lives underwater, though they may also be affected by entanglement. Because it is so hard to observe animals at sea, there may be many animals affected by entanglement that are not counted, because they die at sea and sink out of sight.

Ghost Fishing

Another form of entanglement is known as "ghost fishing." Ghost fishing occurs when fishing gear such as nets or traps is lost at sea. This fishing gear is no longer being used by fishers, but the gear continues to catch fish, crabs, and other animals (Figure 21). If these animals cannot escape, they die of starvation or entanglement-related physical damage. To make matters worse, the dead or dying animals in **ghost nets** or traps attracts predators and scavengers, who then become entangled in turn. One lost net recovered from the western North Pacific was found to contain 99 dead seabirds, 2 dead sharks, and 75 dead salmon.[11]

Ghost fishing is a relatively new problem—before plastic line and netting came into use in the 1940s, all fishing gear was made out of natural fibers such as hemp that would biodegrade if it were lost in the ocean. Now that most fishing nets and traps are made out of plastic material, it can take months to many years for the material to become brittle enough to break down and turn into microdebris. These nets and traps can be hazardous to marine life for years after they are lost at sea.

To try to control ghost fishing, some countries and states require manufacturers to use biodegradable "escape panels" that will eventually break down, allowing marine animals to escape. Another way of preventing ghost fishing is to make it easy for fishers to dispose of old gear properly. One example of this is the "Fishing For Energy" program, a partnership between the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program, Covanta Energy Corporation, National Fish

▶ **Figure 20** A seabird has debris caught on its beak.

▶ © NOAA Marine Debris Program

▶ **Figure 21** A dead seabird is entangled in a ghost net.

U.S. Coast Guard photo by Petty Officer 3rd Class Patrick Kelley and Wildlife Foundation (NFWF), and Schnitzer Steel. Disposing of large amounts of derelict fishing gear can cost a significant amount of money, and fishers understandably do not want to pay to dispose of other people's discarded gear. The "Fishing For Energy" program provides convenient locations for fishers to dispose of derelict gear for free, making them more likely to remove others' lost gear from the environment. The discarded fishing gear is then turned into electricity. Approximately one ton of derelict nets provides enough electricity to power one home for 25 days[12].

Habitat Damage

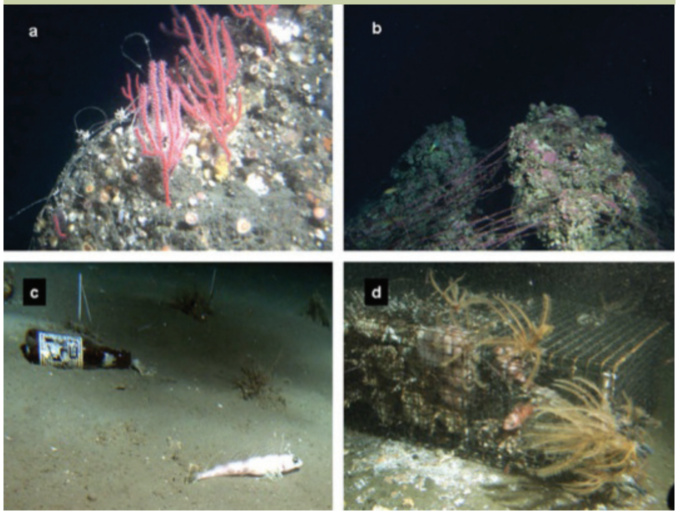
Entanglement can also affect marine habitats (Figure 22). Coral reefs grow slowly and are fragile, and are thus especially vulnerable to damage from lost or discarded fishing gear. In the northwest Hawaiian islands, lost nets were found with many pounds of broken coral fragments tangled in them.[13] In the Florida Keys, lost hook-and-line gear and lobster traps were seen to cause damage to the coral reefs.[10]

Debris resting on the seafloor can affect the bottom-dwelling plants and animals (Figure 23). There is a great deal of debris in the deep sea—one study conducted off central California found 6,900 pieces of debris per km^2.[14] Animals that live in sand or mud can be smothered by large pieces of debris resting on the seafloor.[15] Pieces of trash in the deep sea can change the habitat, providing an advantage to animals that need a hard surface to move in, perhaps at the expense of animals that need a soft surface.

► **Figure 22** A diver removes trash that is damages a coral reef.

▲ NOAA

► **Figure 23** Marine debris rests on the seabed off the coast of central California.



► Reprinted from Marine Pollution Bulletin, Vol 60, Watters et. al., "Assessing Marine Debris in Deep Seafloor Habitats off California," Pages 131–138, Copyright 2010, with permission from Elsevier

Ingestion in Vertebrates

Many animals, including seabirds, marine mammals, sea turtles, and fishes have been found with plastic debris in their stomachs. This can occur either because the animal mistakes the debris for food, or because the animal accidentally ingests the debris during other activities. It is thought that eating plastic can fill the animal's stomach, leading to a feeling of fullness and decreasing the room available for food. Ingesting plastic can also cause intestinal blockage and lacerations, leading to injury or death.

Because it is difficult to measure the stomach contents of a living animal, most scientific studies of this kind have focused on looking in the stomachs of animals that have died, particularly birds, marine mammals, and sea turtles. It is unknown how much plastic exists inside the stomach of animals that are still alive, though some estimates exist from examining animals that died of unrelated causes.

Many species of seabirds have been found to eat plastic (Figure 24). For example, of 24 species of seabirds examined in the central Pacific, 17 were found to have ingested plastic.[6] In nine of those species, more than 80% of individuals contained plastic. Similarly, 21 of 38 seabirds species in the North Atlantic contained plastic.[5] Seabirds also feed plastic to their chicks—one study estimated that more than 90% of Laysan albatross chicks had plastic in their stomach.[16] However, there is not a clear link between plastic ingestion and seabird death. Some studies have found that seabirds with more plastic in their stomachs are less healthy than those with less plastic, while other studies have found no correlation.[17]

Plastic ingestion may be a major cause of death in sea turtles, particularly in juveniles. Studies on dead turtles have found that more than half of dead turtles have plastic in their stomachs.[18,19] Different types of debris causes turtle death in different ways—fishing line with hooks or barbs

Interview with Peter Davison

Graduate Student Researcher, SEAPLEX, Scripps Institution Of Oceanography, UCSD

What are midwater fishes, and why do you study them?

Mesopelagic ("midwater") fishes are small (1–4 inch) marine fishes that live in the "twilight zone" of the ocean. There is enough sunlight for plants to grow in the top 400 feet (150 meters) of the ocean (the epipelagic zone). These plants are the base of the food chain. From 400 feet down to about 3000 feet, sunlight is very dim (the mesopelagic zone). No sunlight penetrates below 3000 feet, and the water column below is called the bathypelagic zone.

The epipelagic zone is occupied by large, fast moving predators that hunt by sight, such as tunas. Since the epipelagic is where most of the food is, many mesopelagic fishes swim to the surface to feed. They do this at night to minimize predation risk. This daily vertical migration is the largest migration in the world.

Mesopelagic fishes include the most common vertebrate on earth, bristlemouths. There are approximately 1 to 10 mesopelagic fishes for every square meter of ocean surface. World-wide, their biomass is estimated to be over 1 billion tons. Because there are so many of them, they are immensely important to pelagic food webs. They are so numerous that their daily vertical migration affects the global carbon cycle. They remove carbon from the epipelagic in the form of food, and carry it several hundred meters down during the day, where it is lost through respiration and defecation. The carbon in the epipelagic ocean is replaced by diffusion of CO_2 from the atmosphere. This is called the biological pump.

Without the biological pump, CO_2 would diffuse out of the ocean and accelerate global warming. Sinking organic material from the surface forms a larger fraction of the biological pump than the active transport by fishes, but I find it very interesting that fish can affect the amount of CO_2 in the atmosphere!

What have you discovered about plastic and fish?

In a nutshell, fish are eating plastic debris that is floating or suspended in the ocean. We found that about 10% of mesopelagic fishes had plastic debris in their stomach. It is unknown whether the plastic harms a fish directly. It is known that hydrophobic toxins such as DDT or PCB adsorb to the surface of the plastic debris, and that these chemicals may be entering the food chain in greater concentrations because of the ingestion of plastic by mesopelagic fishes. The risk of accumulation of toxins is greater for animals at the top of the food chain such as whales, sharks, and seabirds. More research is needed to determine whether or not toxic chemicals are accumulating in the food chain, or if fishes are able to excrete them somehow.

Should we be worried about plastic in the ocean?

Yes, it is not just an aesthetic problem. Fishes, birds, turtles, and marine mammals can become entangled in ghost nets, lost fishing line, or other plastic debris. This often kills the animal. Plastic can alter ecosystems by providing shelter for animals that ordinarily could not survive in the open ocean. These animals may compete with native animals. Plastic can also allow animals to "hitch a ride" across the ocean to become invasive species. We found barnacles, crabs, and bryozoans on plastic debris in the middle of the ocean. Animals such as seabirds, fish, and marine mammals consume plastic, which can harm them in several ways. Plastic debris can also damage ships that encounter it. Plastic washes ashore on coral reefs, and can damage them. It is likely that there are other negative effects that we are not even aware of yet.

can perforate the intestine, while ingestion of plastic bags and **monofilament** line can obstruct the digestive tract.

Marine mammals, such as dolphins and whales, have also been found with plastic in their stomachs. Small cetaceans are known to be affected, such as two pygmy sperm whales found with plastic bags blocking their intestines and three bottlenose dolphins found with monofilament fishing line blocking their throats. The great whales can also be affected by plastic ingestion—in 2008, the deaths of two male sperm whales off California were attributed to ingestion of fishing gear.[20] One of the whales had a ruptured stomach, while the other was emaciated. Researchers found 134 different nets in the stomachs of these two animals.

Microdebris: Ingestion in Small Fishes and Invertebrates

Most life in the ocean is small. Without these tiny plants and animals, larger organisms such as whales would have nothing to eat. The small animals discussed in this section fall into two categories: zooplankton and small fishes. **Zooplankton** are tiny animals found throughout the world's oceans. Many kinds of animals are classified as zooplankton, including tiny crustaceans, jellies, and worms (Figure 25). These animals feed on even tinier plants, called phytoplankton, or prey on each other.

Interview with Andrew Titmus

Graduate Student Researcher,
Hawaii Pacific University

Why should people care about seabirds?

Seabirds are some of the most amazing animals on earth! They undergo some of the largest migrations, often traveling over entire ocean basins in search of food. Seabirds have aided navigators, sailors and fishermen for centuries and still do to this day. As top predators they are ideally placed to sample and gauge the health of our oceans, in terms of ocean condition, fish stocks and pollution.

What is your research about?

I am primarily interested in human impacts on seabird populations including issues of marine debris, fisheries and other pollution in the marine environment. My research is focused on using seabirds as monitors of marine debris. I am examining the patterns in plastic ingestion by North Pacific albatrosses and the oceanographic mechanisms that influence plastic distribution in the North Pacific, as well as developing visual methods to survey marine debris at sea and investigating spatial patterns of both debris and seabirds in the North Pacific.

What have you discovered about plastic and seabirds?

I have found that both amounts and types of plastic ingestion are very variable within North Pacific albatross species. Different species ingest different types of plastic as is to be expected from differences in foraging strategies, however, the amount and types of plastic ingested varies by colony location. This serves to indicate that broad based approaches based on multiple species, and multiple locations are needed to be able to use seabirds as indicators of marine debris.

► **Figure 24** Remains of Laysan albatross chick that had been fed plastic by its parents.

► Photo from USGS

► **Figure 25** Zooplankton viewed through a microscope.

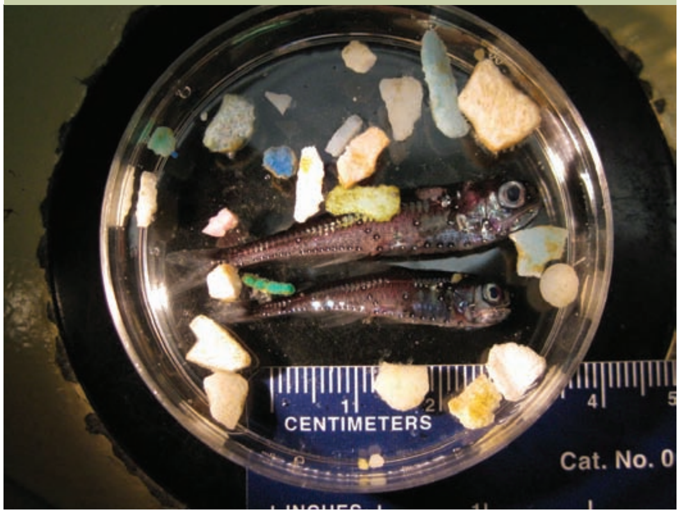
► © 2009 Scripps Institution of Oceanography/UC San Diego.

It is not known if zooplankton are ingesting microdebris in the ocean. This has been studied in the laboratory, but not in natural ecosystems. In the laboratory, several types of zooplankton readily eat plastic, but the plastic was released in their fecal pellets and appeared to cause no acute harm to the organisms.[21] This research means that zooplankton are able and willing to ingest plastic particles, but potential negative effects are uncertain.

In laboratory studies on microplastic ingestion in bottom-dwelling invertebrates, researchers found that these animals ate plastic as well. When kept in aquaria with plastic particles, lugworms, amphipods, and barnacles ingested plastic within a few days.[22] Sea cucumbers also ate plastic particles in the laboratory.[23] More disturbingly, when blue mussels ate plastic, the particles showed up in their blood up to 48 days after being eaten.[24] As with the zooplankton, none of these organisms in these studies appeared to be harmed by the plastic, but this may have been because all the studies were relatively short-term.

Microplastic may also be eaten by small fishes (Figure 26). These fish naturally prey on zooplankton, and since a great deal of microdebris is the same size as zooplankton, they may mistake plastic for food. Research conducted on the Scripps Environmental Accumulation of Plastics expedition found plastic in about 10% of the stomachs of small fish. (See interview with researcher Peter Davison, page 20). Another study found that the stomachs of fur seals contained plastic particles too small for the seals to have eaten, suggesting that the particles had originally been inside fish that had been eaten by the seal.[25]

▶ **Figure 26** Small lanternfish were caught along with microdebris. Lanternfish are one type of fish known to ingest plastic.



Microdebris: Toxins

When either large or small animals ingest plastic debris, toxins present on or in the plastic has the potential to pass into their bodies. These toxins can be either part of the plastic, or absorbed into the plastic from the surrounding seawater.

Toxins that leach out of the plastic and into the ocean include plasticizers. Plasticizers are substances added to the plastic to changes its physical characteristics, such as to make it more flexible. Plasticizer molecules may be released into organisms via ingestion or into the environment through the degradation of plastic. Plasticizers have been detected in **landfill leachate**, sewage outflow, and particles collected from the North Pacific Subtropical Gyre.[26]

Though there are many types of plasticizers, phthalates and BPA have been most studied due to their association with food products and baby bottles. Phthalates and BPA have been shown to affect reproduction in laboratory animals, and to induce genetic abnormalities.[27] In small mammal studies, plasticizers have been associated with testicular abnormalities and other reproductive disorders as well as thyroid disease.[28] In humans, phthalates and BPA may be associated with altered endocrine function and have negative reproductive or developmental effects in humans, though studies are limited.[29]

As the plastic floats in the ocean, certain chemicals start to “stick” to it. This process is called **adsorption**. Small particles of plastic can adsorb pollutants at concentrations up to a million times higher than those found in the surrounding seawater. These pollutants include the pesticide DDT and its breakdown products, the flame retardant PBDEs, and the banned industrial chemical PCBs. These pollutants can cause many problems in living organisms, including immune deficiencies, endocrine disruption, behavioral changes, nerve damage, and cancer.

Researchers are currently determining whether these pollutants can pass from plastic particles into the bodies of animals that are ingesting plastic (Figure 27). Research is ongoing, but one study, done with birds in the laboratory, found that birds that ingested plastic did have higher levels of pollutants in their bodies.[26] Since, as we discussed in the above section, many species of animal ingest plastic debris, plastic-associated toxins have the potential to damage marine life. If these toxins are being passed up the food chain, these chemicals also have the potential to impact people who eat seafood. However, there is very little scientific data on the impact of plastic-associated toxins on the marine food web.

Rafting and Introduction of Invasive Species

Most species in the open ocean are adapted to living without any hard surfaces around. The bottom is miles away, and the only substance that surrounds them is water. However, there are a few naturally occurring hard surfaces in the ocean, including algae, pumice, and wood, and these have provided a habitat for a specialized community of animals.[30] Since these surfaces act as rafts, these communities are called “rafting communities.”

Rafting communities are relatively common in the North Atlantic due to the seaweed *Sargassum*, which floats in the middle of the ocean and provides a home for many animals, such as crabs, fish, and small crustaceans. However, rafting

▶ **Figure 27** SEAPLEX graduate student toxicologist Chelsea Rochman collects plastic debris for laboratory analysis with a dip net.

communities in the Pacific are more rare because there is little naturally occurring surface.

The increase of plastic debris in the world's ocean has vastly increased the surfaces available to these rafting communities (Figure 28). Pelagic plastic debris is ideally suited for rafting due to its abundance, buoyancy, and persistence, and has rapidly become a common substrate. Rafting on plastic debris has been observed all over the world, and increases with supply of plastic debris. For example, though rafting is usually rare in the Southern Ocean due to low temperatures and large waves, rafting on plastic debris has been observed.[31]

While it might seem positive that plastic debris is providing habitat for marine life, this is actually a reason for concern. Invasive species, species which are transported out of their original habitats into a new one, cause millions of dollars of damage worldwide. Invasive species can interfere with the growth and development of native species by eating or outcompeting them, alter nutrient availability or water quality, and impact fisheries and aquaculture operations. For example, the invasive European green crab has an estimated economic impact of $44 million per year due to the damage that it causes commercial shellfish operations.[32]

Rafting on plastic debris could introduce invasive species to sensitive marine habitats. The particular vulnerability of island ecosystems to invasions and the large amount of plastic debris collecting on the mid-Pacific islands (such as the Papāhanaumokuākea Marine National Monument) makes transport of rafting species a matter of particular concern in the North Pacific. Because debris moves slowly with the currents, it may be the case that rafting animals will arrive on these islands in good condition, ready to become invasive species.

Rafting communities on plastic may also host different species from rafting communities on natural substrates such as wood. Artificial substrates can have lower biodiversity than natural substrates. This may favor species that are able to grow on plastic debris, causing them to increase their numbers and potentially have a negative impact on other species.

Most studies have examined beached debris or ghost nets, not microdebris. The composition of rafting communities on microplastic is currently being studied.

Can It Be Cleaned Up?

While very expensive, it is relatively straightforward to clean up macroplastic. Cleanup efforts, particularly focused around discarded fishing gear and ghost nets, are ongoing in areas such as the Northwest Hawaiian Island and Puget Sound. In the Northwest Hawaiian Islands, NOAA regularly removes ghost nets from isolated beaches and coral reefs (Figure 29).

Cleaning up microplastic is extremely technically challenging. As discussed earlier, the particles of plastic are the same size as the zooplankton that make up much of the life

► **Figure 28** Gooseneck barnacles and anemones grow on a piece of line collected from the North Pacific Subtropical Gyre during the SEAPLEX expedition.

▲ © 2009 Scripps Institution of Oceanography/UC San Diego Photo credit: J. Leichter.

► **Figure 29** Divers removing a ghost net from a coral reef.

► © NOAA PIFSC

in the ocean. It would be very difficult to remove microplastic without removing a substantial amount of zooplankton, small fishes, and other marine life. The area that would need to be cleaned is truly vast. For example, the North Pacific Subtropical Gyre alone is more than three times the size of the United States. Removing tiny particles from this immense stretch of ocean would be time consuming and extremely expensive.

This is not to say that cleanup is impossible, but these technical challenges would need to be surmounted. For now, prevention is best.

What Else Is Being Done?

Technological solutions

Alternative plastics that are more easily biodegradable have been developed. The most widely used biodegradable plastic is called **polylactic acid (PLA),** and is made from cornstarch. While PLA does break down in industrial compost facilities like that in the city of San Francisco, it does not degrade in backyard composts, landfills, or the environment.[33] If PLA containers are mixed with regular recycling, the PLA can actually contaminate the recycling equipment, leading to less overall recycling.[34]

Many other biodegradable plastics are in development, though none are in wide use as of yet. One of these is Mirel, which the manufacturers claim will break down in the ocean. Another is a biocomposite that fuses natural fibers with degradable plastic, which is designed to break down easily in low-oxygen environments such as landfills.[35]

Legislation

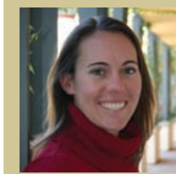
Many countries, states, and cities have instituted legislative bans or taxes on various plastic products. Countries that have banned free plastic bags include Rwanda, Bangladesh, China, and Germany, and countries that tax plastic bags include Ireland, Israel, Denmark, and Taiwan.

The United States has no federal or state bans on plastic products. Though there have been eleven proposed statewide bans in the past two years, all have failed to pass. In lieu of federal or state legislation, some cities have instituted bans or taxes. Plastic bags are banned in San Francisco, CA; Bethel, AK; Edmonds, WA; and the Outer Banks of North Carolina. Plastic bags are taxed in Washington, DC; Santa Monica, CA and other cities in California have banned polystyrene ("Styrofoam") containers, and Concord, MA has banned plastic water bottles.

While there are not yet scientific studies on the impact of banning or taxing plastic bags, the media reports that these measures can decrease plastic bag use. In Ireland, the plastic bag tax was reported to cut usage by more than 90%, and charging a small fee for plastic bags cut usage by half in both China and Washington, DC.[36–38]

Interview with Alicia Glassco

Marine Debris Coordinator, San Diego Coastkeeper



What is your job at Coastkeeper?

I manage the Marine Debris Program for San Diego Coastkeeper, a nonprofit organization working for clean water in San Diego County by education, restoration, and advocacy. We help restore our coastal habitats by facilitating cleanups with over 12,000 volunteers removing over 100,000 pounds of debris from beaches, bays, and inland canyons each year. We educate the public through community events like movie screenings and lectures and by teaching volunteers to collect data while cleaning up their beach. We also advocate for improved trash policy by connecting with decision makers about the types of trash we record, and finding ways to stop litter before it reaches the ocean.

What do you think is the best way to keep plastic out of the ocean?

We now know how truly damaging plastics can be to our marine ecosystems, that most the trash is coming from land, and that 8 of the top 10 items our volunteers record on their beach cleanup data sheets are composed of plastic. So reducing the types of plastic that are made of toxic materials and easily discarded into the environment is an important focus of our program. Generally, we focus on reducing single-use disposable plastic items such as plastic bags, expanded polystyrene (or Styrofoam®), plastic bottles and caps, cigarette butts. The best way to do this will be through appropriate policies controlling this type of pollution and increased responsibility by producers and retailers for their products which end up harming the marine environment.

What can people do to help fight marine debris?

Everyone can make a difference when it comes to reducing trash in your neighborhood and environment. Even if you don't live right on the beach, get involved in community cleanups, never litter, choose reusable items over single use plastics, communicate litter issues to your local government, and always speak up if there is an important policy on the line that would help reduce trash in our oceans. Environmental organizations like San Diego Coastkeeper are an important conduit to get involved in these actions, so contact your local group and make a difference in your community!

Prevention

While some marine debris comes from ocean-based sources such as fishing gear, some marine debris also comes from land. Litter enters the ocean from coastlines around the world, and since plastic does not biodegrade, most litter that enters the ocean stays in the ocean. One of the most effective ways of controlling marine debris is to prevent it from entering the ocean in the first place.

Beach cleanups are a popular form of prevention (Figure 30). By removing trash from beaches and waterways, trash can be prevented from going into the ocean. A well-known and popular cleanup day is the International Coastal Cleanup, organized by the Ocean Conservancy, which takes place each year on one day in late September. In 2009, nearly a half-million people from 108 countries removed 7.4 million pounds of debris. Over 10 million individual pieces of trash were counted. The most common type of trash was cigarette butts, with plastic bags trailing a distant second.[39]

Another prevention approach is to increase recycling rates by improving infrastructure, making it easier for people to recycle. Currently, only 7% of all plastics are recycled, in large part because many municipalities only accept recycling number 1 and 2 (PETE and HDPE).[40] The industry trade association, the American Chemistry Council, has installed recycling containers at beaches and put out public service announcements encouraging people to recycle.

The most popular prevention approach is education and outreach efforts focused on improving public understanding of the problem of plastic in the world's oceans. These efforts hope that if people understand the scope of the problem, they will reduce the amount of plastic used in their daily lives and refrain from littering. Some of the most dramatic examples of education and outreach efforts were two boats constructed of repurposed plastic trash. In 2008, the Junk Raft sailed from California to Hawaii, and in 2010 the Plastiki sailed from California to Australia. Both vessels used an adventure to communicate a plastic-reduction message to the public. Another effort was the "I'm Not A Plastic Bag" reusable shopping bag designed by Anya Hindmarch. This bag sold out of London stores just hours after it was released, was featured in fashion magazines, and may have reached a fashion-conscious audience not normally involved in conservation efforts.

▸ **Figure 30** International Coastal Cleanup

▸ © NOAA Marine Debris Program/Ocean Conservancy

What Can You Do?

In this chapter, you have learned that plastic trash entering the ocean can break down into smaller pieces through the action of sun and waves, but that plastic does not biodegrade. Plastic pollution has been found in the open ocean for at least 40 years, and may be damaging marine ecosystems through entanglement, ingestion, toxins, and invasive species introduction.

While some marine debris comes from the fishing and shipping industries, much of the plastic found in our oceans is thought to be from consumer products—the everyday objects such as plastic bags and disposable water bottles used by people around the world. No matter where you live, you can help stop marine debris by disposing of your own trash properly, picking up litter, and reducing, reusing, and recycling the plastic products in your own life. If we all do our part to prevent trash from entering the ocean, future generations may not have to worry about marine debris.

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